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Sound Environment Between Parallel Barriers and In Cuts

J.J. Hajek
Project Research Officer
Research and Development Branch

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The Editor
Research and Development Branch
Ministry of Transportation and Communications
1201 Wilson Avenue
Downsview, Ontario
M3M 1J8

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Abstract

The sound environment between parallel barriers and in cuts has been analytically evaluated and compared with measured data. Results indicate that principles of geometrical acoustics are applicable, in particular by defining image sources to account for sound reflections. Such principles can be used successfully for describing fields of highway sound reverberation. It is postulated that this technique should also be reliable for estimating sound levels outside (behind) barrier walls where verification by field measurements is more difficult.

SOUND ENVIRONMENT BETWEEN PARALLEL BARRIERS AND IN CUTS

1/ Introduction

The objective of the work reported herein was to obtain a better understanding of the effect of multiple reflections due to parallel highway noise barriers. Opposing barriers, or highway cuts with retaining walls on both sides, can give rise to multiple reflections. The resulting reverberation field within barrier walls can significantly affect sound levels both within barrier walls and outside (behind) barrier walls.

The effect of parallel barriers for receivers located outside barrier walls was recently investigated using geometrical acoustics [1]. Results indicate that under certain conditions, sound levels calculated for locations shielded by parallel barriers may actually be higher than sound levels calculated for corresponding locations in free field (i.e. not shielded by any barriers).

The degradation effect of parallel barriers (i.e., the reduction in barrier insertion loss due to the presence of an opposite barrier) is difficult to verify by direct field measurements. At large distances behind the barrier, where the degradation effect reaches measurable proportions (i.e., 3 or 4 dB), sound levels can easily be influenced by highly variable community noise sources and by weather related factors [2]. Also, ever present large reflecting surfaces such as houses, highway vehicles, and parapet walls, further mask the degradation effect of opposing barriers.

The sound field between barrier walls can be assessed more easily. The influence of community noise sources and reflective surfaces from outside barrier walls is insignificant. Analytical modelling is simplified and calculated results can be readily verified by simultaneous measurements of sound levels at a location between walls and at a corresponding location without walls. The understanding of sound environment between barrier walls is important for three reasons:

i) Understanding of the reverberation sound field between walls, its prediction and verification by direct measurements, leads to a better understanding of the sound field behind barrier walls where residents are located.

ii) The reverberant sound field between walls can affect highway users. Higher sound levels may result not only in user annoyance but can also obscure driver perception of the relative distances between vehicles [3].

iii) It enables assessment of the influence of design variables such as sound absorptive treatment and wall geometry.

2/ MATHEMATICAL FORMULATION

A number of theories can be used to describe a reverberant field in enclosed or semi-enclosed spaces; namely, wave reflection theory, diffuse field theory, and application of geometrical acoustics based on image theory. The geometrical acoustics method was used in this study due to its simplicity and reported reliability [4,5].

As illustrated in Figure 1, the walled highway is represented as a channel between two infinite sound reflecting planes. In the center of the channel is a single point source, S, emitting sound energy at a constant rate and frequency spectrum. Sound waves can reach a receiver, R, both directly and after one or more reflections off side walls. These reflections can be represented by two infinite sets of image sources, each situated on one side of the channel. The space within the channel is referred to as the reverberant field. The corresponding space not bounded by the channel walls is referred to as the free field.

The objective of the mathematical model was to obtain a difference between the free field sound levels and the reverberant sound levels. For this reason, only the variables affecting the difference between the sound intensity of the free and reverberant fields were included in the model.

Reflection of sound waves, and their propagation over partially reflecting planes, are complex phenomena [6]. To obtain a numerical solution, several assumptions were required:

i) Only specular reflection exists with no incident sound power scattering. Loss of sound energy, due to reflections off the wall surfaces, is accounted for by an absorption coefficient.

ii) The absorption coefficient does not depend on angle of incidence (i.e., absorption coefficient is the same for all reflections) and is constant over the entire frequency range of highway noise which contributes significantly after A weighting is applied.

iii) The walls are high enough relative to (a) the position of the source and the receiver above ground, and (b) source wave length, to enable a full reflection.

iv) The contributions of real and image sources are added incoherently.

v) The source exhibits a uniform directivity pattern.

The total sound intensity at the receiver, Itot, can be obtained by adding sound intensity reaching the observer directly, Iff, and sound intensity reaching the observer after one or more reflections, Irev. The increase in sound intensity level, ΔL, due to reflections can be expressed as:

$$\Delta L = 10 \log \frac{Itot}{Iff} \qquad (1)$$

where ΔL = Difference between total sound intensity and free field sound intensity in decibels.

Itot = Sound intensity, watts/m^2. Itot = Iff + Irev

Sound intensity of a point source at a distance, d, from the source, assuming spherical spreading and a perfectly reflecting ground, is given by:

$$Iff = \frac{S}{4 \pi d^2} \qquad (2)$$

where S = Sound power in watts

d = Straight line path length between the source and the receiver, m.

Since an infinite number of reflections exist for the source-receiver configuration shown in Figure 1, the total sound intensity can be obtained by adding all contributions:

(3)

$$Itot = \frac{S}{4\pi} \sum_{n=o}^{n=\infty} c \frac{(1-\alpha)^n}{d^2 + (nw)^2}$$

where

n = Number of reflections; n = 0,1,2,3...

α = Sound absorption coefficient (identical for both barrier surfaces)

c = Coefficient accounting for the symmetry of image sources.

c = 1 for n = 0

c = 2 for n $\neq$ 0

w = Distance between parallel walls

Substituting Equations 2 and 3 into Equation 1 we get:

$$\Delta L = 10 \log\left[1 + 2d^2 \sum_{n=1}^{\infty} \frac{(1-\alpha)^n}{d^2 + (nw)^2}^2\right] \quad (4)$$

Equation 4 was expanded to include the attenuation of sound resulting from atmospheric absorption. The rate of energy decay due to atmospheric absorption was assumed as a path-length dependant constant of 0.001772 dB/m. This rate was recommended in Reference 7 for frequency of 500 Hz, ambient temperatures around 20°C, and relative humidity in the range of 50% to 70%. The frequency of 500 Hz was chosen since this frequency often dominates A-weighted traffic noise spectra.

Including the effect of atmospheric absorption in Equation 4 we get:

$$\Delta L = 10 \log\left[1 + 2d^2\ 10^{Ed} \sum_{n=1}^{\infty} \frac{(1-\alpha)^n}{d^2 + (nw)^2} \cdot \frac{1}{10^{E\sqrt{d^2+(nw)^2}}}\right] \quad (5)$$

where

E = Atmospheric absorption coefficient, 0.001772 dB/m.

Equations 1,2 and 3 were also used to obtain total sound level, Ltot, in absolute terms.

After including the atmospheric absorption coefficient we get:

$$L_{tot} = 10 \log \left\{ \frac{S}{2\pi I_o} \left[\frac{K}{2d} + \sum_{n=1}^{\infty} \frac{(1-\alpha)^n}{\sqrt{d^2 + (nw)^2}} K^1 \right] \right\} \quad (6)$$

where

I_o = Reference power intensity, 10^{-12} watts/m^2

$$K = \frac{1}{d \; 10^{Ed}} \quad (7)$$

$$K^1 = \frac{1}{\sqrt{d^2 + (nw)^2} \; 10^{E\sqrt{d^2 + (nw)^2}}} \quad (8)$$

Several factors affecting only the total sound energy or its time variation, and not affecting the difference between sound energy in the reverberation field and sound energy in the free field, are not included in Equations 5 and 6:

i) Contributions due to pavement (ground plane) reflections. The omission of pavement reflections is considered negligible since the first pavement reflection would exist in both fields:

ii) Effect of motion on the sound radiation. (Excellent discussion of this topic can be found in Reference 8.)

iii) Effect of retarded time, i.e., time at which the observed sound was emitted by the source. Sounds travelling on different propagational paths would not reach the receiver simultaneously. However, the total sound energy reaching the receiver over a period of time is not affected.

3/ COMPUTER SIMULATION

Equation 6 defines Ltot for only one distance from the source. To obtain a passby curve of a point source passing a receiver in the reverberant field, Ltot must be known for all distances. Equation 6 assumes that the source and the receiver are located on the source path. However, Ltot depends, particularly for short distances between the source and the receiver, on the position of source and receiver in relation to boundaries. For this reason, Equation 6 was modified to distinquish the receiver location from the source path (see Figure 2) and the numerical solution was computerized.

Figure 3 shows typical single point source passby curves calculated for the free field and for the reverberation field. In the case of the reverberation field, the distance between the two barrier walls is 30 m and 60 m. Also shown is the effect of atmospheric absorption which becomes noticeable only for greater distances from the source.

Data in Figure 3 and other similar data were obtained by considering the first 15 reflections only. This is not a limitation imposed by the program. The number of reflections included in calculations was based on practical considerations. The contribution of the next 85 reflections (16th to 100th reflection) was less than 10% of the values obtained for the first 15 reflections even for the sound absorption coefficient of the walls $\alpha = .05$.

The difference between sound levels in the reverberation field and in the free field is independent of the sound power of the single point source (see Equation 5). Moreover, it is also independent of the number of single point sources, provided that their number, intensity, and position relative to the walls is the same for both fields. Thus, by integrating sound energy of the single point source passby curves in the reverberant field and in the free field, and then calculating the difference between them, we can obtain the difference in sound energy

between the two fields for the total traffic flow, ΔL_{eq}. This was accomplished by means of numerical integration of the expression:

$$\Delta L_{eq} = 10 \log\left[\frac{1}{X}\int_{-x}^{+x} Ltot\ (x)\ dx\right] - 10 \log\left[\frac{1}{X}\int_{-x}^{+x} Lff\ (x)\ dx\right] \quad (9)$$

where

X = Length of reverberation field assumed to be symmetrical with respect to the receiver

x = Interval of distance

The difference between sound energy levels in the reverberation field and in the free field, ΔL_{eq}, was evaluated over an integral of distance rather than time. Thus, the influence of the width as well as length of the reverberation field could be directly quantified.

Some of the results obtained by evaluating Equation 9 are shown in Figure 4 which relates L_{eq} to the distance between walls and to the sound absorption coefficient of the walls. It is apparent that the sound absorption coefficient, α, is an important parameter influencing sound energy build-up within walls. For example, ΔL_{eq} for partially sound absorbing walls (α=0.5) 10 m apart is similar to ΔL_{eq} for sound reflective walls (α=0.05) 70 m apart. The sound energy build-up within walls can also influence sound levels outside of them, behind barrier walls or retaining walls.

4/ EXPERIMENTAL RESULTS

To verify the mathematical model, two types of full-size experiments were conducted:

a) Measurements of passby curves of single vehicles
b) Measurements of total highway traffic flow

4(a)/ Comparison of Passby Curves of Single Vehicles

Passby curves of single vehicles were measured along a relatively flat 6-lane freeway using two heavy diesel trucks. The trucks were passing at a constant speed of 80 km/h at two adjacent receiver points: The first receiver point was located within a reverberation field formed by two 6 m high retaining walls and the second receiver point was located in a free field with no reflecting surfaces, such as houses or parked vehicles, within a 90 m radius. The retaining walls were of untreated concrete with a coefficient of absorption, α, estimated at 0.05. Figure 5 shows a schematic diagram of the experimental set-up including a cross-section of the reverberant field.

In Figure 6, measured time histories for both free and reverberant fields are compared with calculated time histories for a typical passby test. The measured sound levels in this figure are dBA levels; the calculated sound levels are for a frequency of 500 Hz and are comparable (for highway noise) to the measured dBA levels (see Section 2). Sound levels are not given in absolute terms because of difficulties in identifying acoustic power of the testing trucks. At any rate, we are interested in differences between the sound levels in the free field and the reverberant field rather than in their absolute values. Figure 6 shows a very close agreement between the measured and the calculated time histories, disregarding considerable fluctuations of measured values. The fluctuations are a result of ground interference, wall reflections, turbulence and other factors which were not included in the mathematical model.

In addition to the time histories which are somewhat difficult to evaluate due to the instantaneous fluctuations, maximum sound levels were also evaluated. The maximum sound levels of the testing trucks were measured using the same measurement set-up used for the measurement of time histories (Figure 5). The measurement in the reverberation field was, of course, close to the reflecting surfaces and the distance from the vehicle's centerline was 24.7 m, but otherwise all instrumentation test site conditions defined in SAE J57a (9) were met. The average measured difference between maximum sound levels emitted by the testing trucks in the reverberation field, and in the free field, was 4.8 dBA. The corresponding calculated difference was 3.3 dBA.

4(b)/ Comparison of Total Traffic Flow

Experimental measurements of the total traffic flow were conducted on the same site (see Figure 5), and using similar procedures, as the measurements of single vehicles. In addition, measurements were also conducted on a site along an 8-lane freeway. Two microphones were used simultaneously at both sites; one located within a reverberation field and the second located in a free field. Traffic flow volume, composition and speed, pavement type, distance between receiver and traffic lanes, and other factors were identical at both locations. Consequently, the difference between the sound levels obtained at the two locations could be attributed solely to the effect of parallel reflecting walls.

Results were expressed in terms of highway traffic noise descriptors used for planning purposes, such as: L_{eq}, L_{10} (sound level exceeded 10% of the time), L_{50} and L_{90}. Results for the 6-lane freeway are summarized in Table 1.

The data of Table 1 show that noise descriptions related mainly to peak sound levels, L_{10} and L_{eq}, are not as affected by the reverberation field as noise descriptors related mainly to average and background sound levels, L_{50} and L_{90}, respectively.

For example, the difference between the reverberant and the free field was about 3 dBA in terms of L_{eq} levels while the corresponding difference in terms of L_{90} levels was about 8 dBA. This is not surprising considering the passby curves shown in Figures 3 and 6. For a single vehicle passby, the difference between sound levels in reverberant and free fields increases with the distance from the closest approach. This tends to affect background levels more than peak levels.

The changes in the reverberant sound field cannot be characterized only by an average increase in sound levels. The time distribution of sound levels is also changed since peaks and background levels are increased at different rates. This is important when considering a driver's perception of other vehicles on the road. When the peak sound levels of individual vehicles are increased, they may be perceived by a driver as being closer than they actually are. However, the increase in the peak level is masked by even higher increase in the background levels. Because of these two conflicting trends, the driver's hearing perception of other vehicles on the road should not be significantly affected. The actual perception of the driver depends also on the sound levels emitted by the driver's own vehicle, its sound insulation characteristics, the density and composition of traffic flow and on other variables.

Figure 7 compares frequency spectra measured simultaneously in the free field and in the reverberant field. Sound pressure levels in the reverberant field are generally higher for all frequency bands. However, the increase is lower for higher frequencies, approximately above 2000 Hz. The smaller increase obtained for frequencies above 2000 Hz may be attributed to higher atmospheric absorption and to the influence of the reflection-scattering process.

Figure 8 shows calculated and measured differences between sound levels in the reverberant and the free fields. The comparison is in terms of L_{eq} levels; the measured levels are dBA levels, the calculated levels are for frequency of 500 Hz. The measured data were obtained for a 6-lane freeway (Hwy. 409, Figure 5) and for an 8-lane freeway (Hwy 427). The measured differences are lower than calculated ones by about 1 or 2 dBA. Considering approximations and assumptions used in the mathematical model, this is quite a reasonable agreement. Discrepancies could arise for example, from non-uniform directivity pattern of highway vehicles, shielding by highway vehicles, reflection-scattering process, incoherent summation of the image source contributions and from experimental error. Also, in the case of the 8-lane highway, the length of the reverberation field was only about 400 m, rather than 1500 m as assumed in calculations.

5/ CONCLUSIONS

1. A close agreement was obtained between the measured and predicted sound levels in a reverberation field formed by opposing highway walls. Predictions were based on geometrical acoustics, employing image sources to account for multiple reflections.

2. Since the image source theory provides reliable results for the sound field within barrier walls, it should also provide reliable results for the sound field outside (behind) barrier walls. However, verification of calculated results behind barrier walls by field measurements is more difficult.

3. The peak sound levels of single vehicles within walls can be significantly increased due to multiple reflections. At the same time, the background sound levels are increased even more. Thus, the increase in the peak levels is masked by an even higher increase in the background levels. The driver's perception of noise source location should not be significantly affected.

4. Simple design curves for estimating impact of multiple reflections between walls, as a function of distance between walls and wall sound absorption coefficients, were developed.

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Table 1/ COMPARISON OF SOUND ENVIRONMENT IN REVERBERATION FIELD AND IN FREE FIELD, HWY. 409

Parameter	Sound Descriptor, dBA			
	L_{eq}	L_{10}	L_{50}	L_{90}
Number of Measurements*	11	11	11	11
Average difference between reverberation field and free field, dBA	3.07	4.44	6.74	8.32
Standard deviation of differences between reverberation field and free field, dBA	1.32	1.23	1.35	1.52

* All measurements were 20 min in duration.

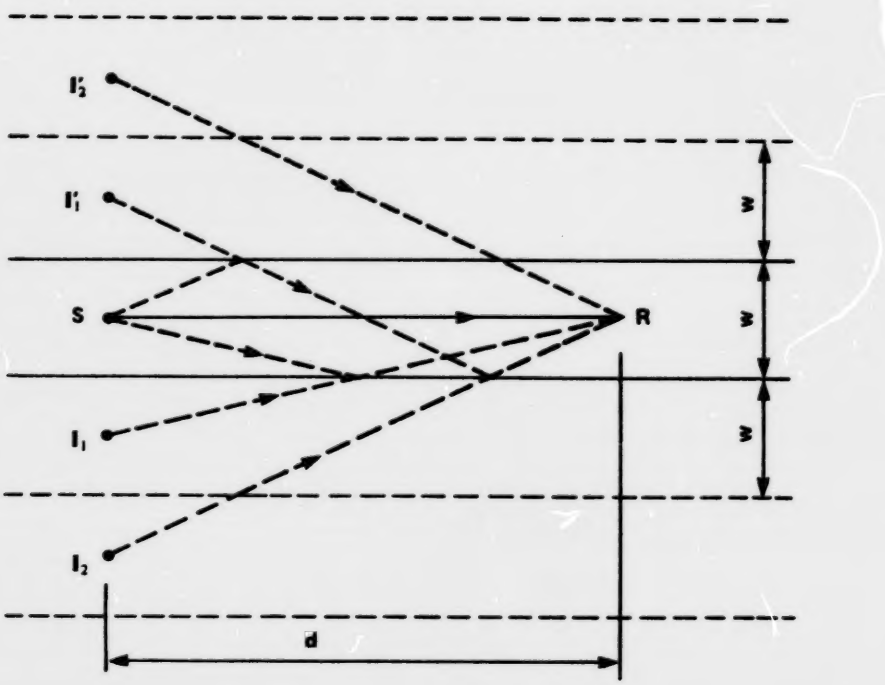

Figure 1/ Construction of Image Sources.
Image sources exist in two discrete pairs; eg. I_2 = image source for the second reflection and the first pair. w = distance between walls; d = distance from source to observer.

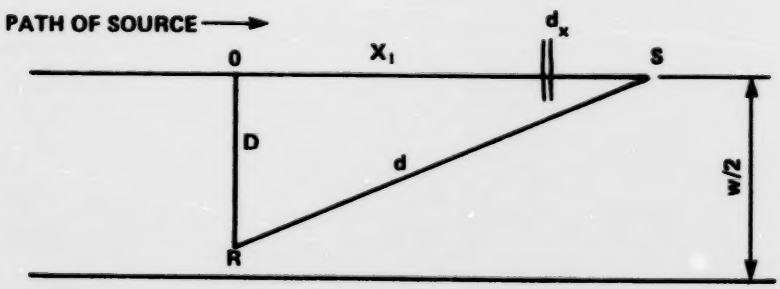

Figure 2/ Parameters for Calculation of Passby Curves
D = distance of closest approach, d = actual path length between source and receiver.

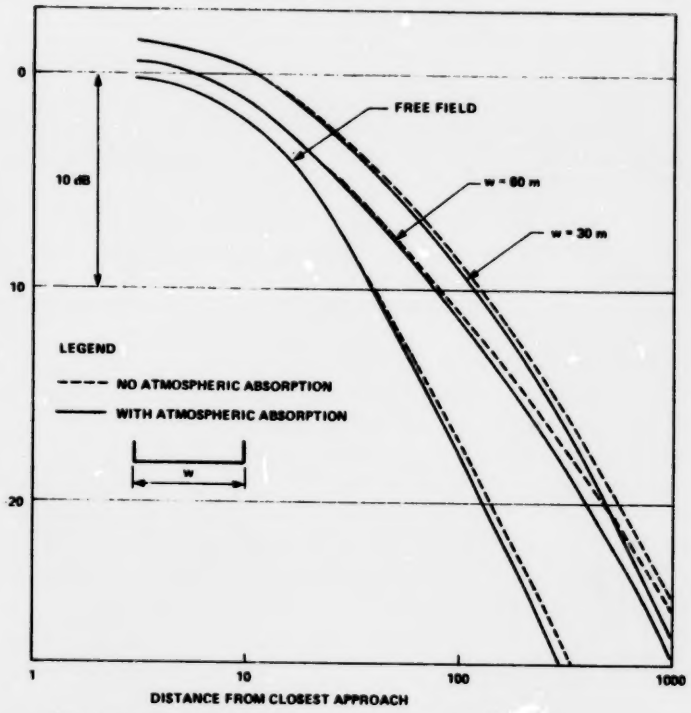

Figure 3/ Single Point Source Passby Curves.
Absorption coefficient of walls, α = 0.05; Distance to closest approach, D = 13.0 m; Number of reflections accounted for, n = 15; Coefficient of atmospheric absorption E= 0.001772 dB/m.

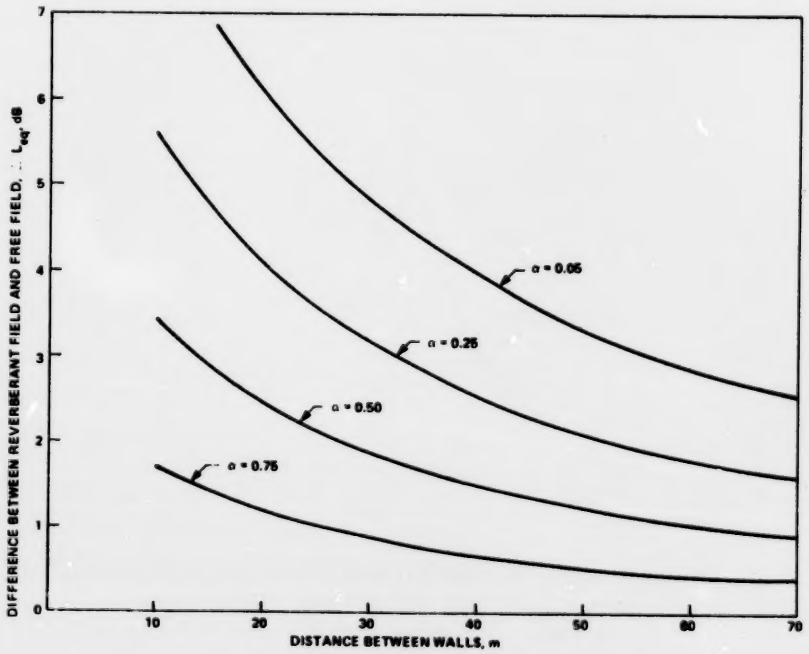

Figure 4/ Increase of Sound Levels in Reverberation Field
Sound absorption coefficient of walls, α, varies; Distance to closest approach, D = 13.0 m; Number of reflections accounted for, n = 15; Coefficient of atmospheric absorption, E = 0.001772 dB/m; Length of reverberation field, λ = 1500 m.

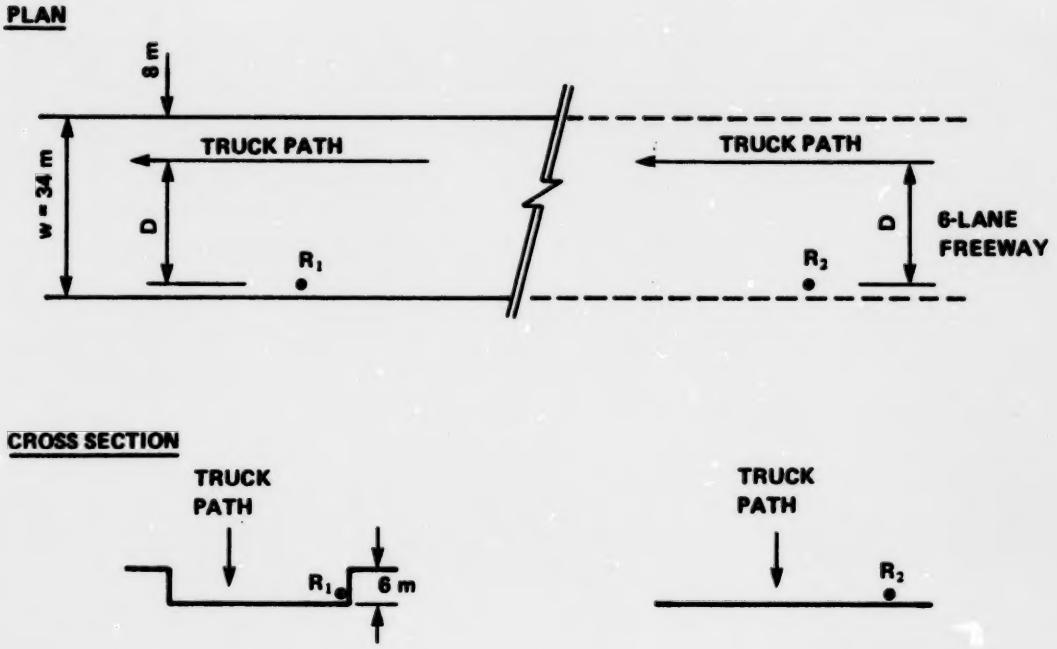

Figure 5 / Schematic Diagram of Measurement Set-Up, Hwy 409

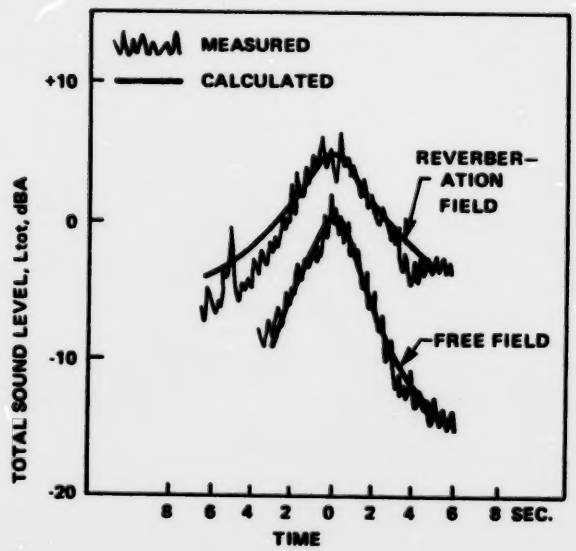

Figure 6/ Comparison of Measured and Calculated Passby Curves.
Conditions: Speed of test vehicle 80 km/h;
Distance to closest approach, D = 24.7 m;
Number of reflections accounted for, n = 15;
Coefficient of atmospheric absorption, E = 0.001772 dB/m;
Length of reverberation field 1500 m; Its width, w = 34 m;
Sound absorption coefficient of walls, $\alpha = 0.05$.

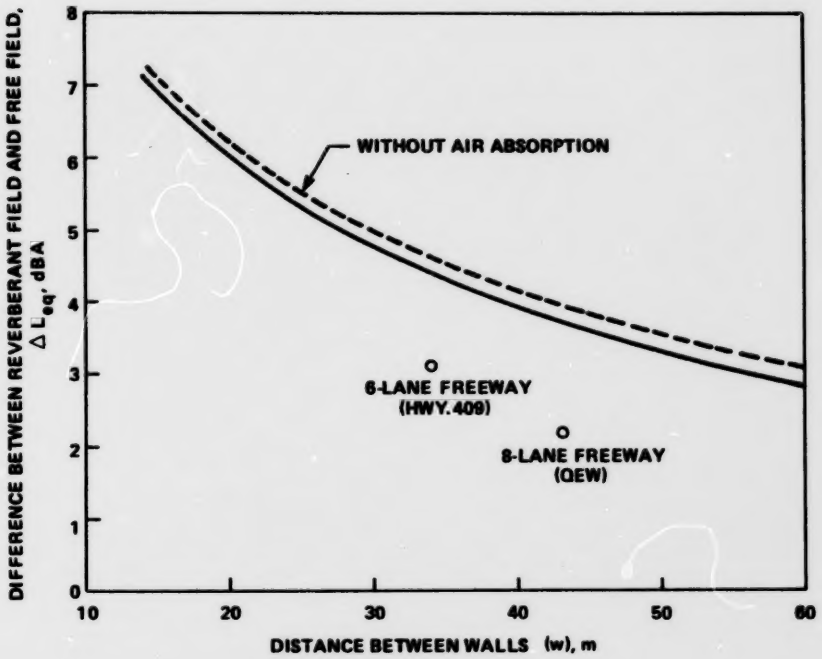
DIFFERENCE BETWEEN REVERBERANT FIELD AND FREE FIELD, ΔL_{eq}, dBA
WITHOUT AIR ABSORPTION
6-LANE FREEWAY (HWY.409)
8-LANE FREEWAY (QEW)
DISTANCE BETWEEN WALLS (w), m

Figure 8/ Comparison of Measured and Calculated Differences Between Reverberant Field and Free Field.
Calculations are based on: Sound absorption coefficient of walls, $\alpha = 0.05$; Distance to closest approach, D = 13.0 m; Number of reflections accounted for, n = 15; Coefficient of atmospheric absorption, E = 0.001772 dB/m; Length of reverberation field, X = 1500 m.

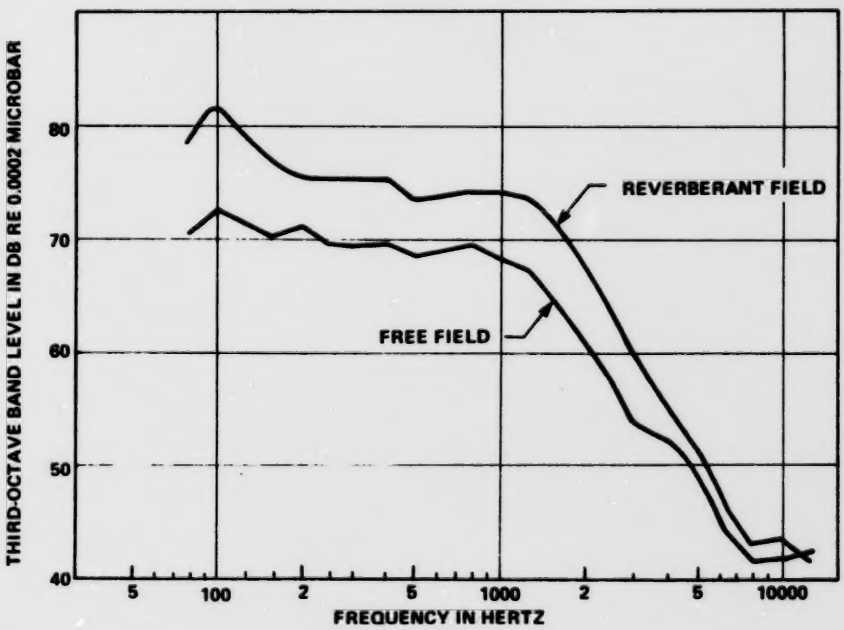

Figure 7/ Comparison of Frequency Spectra Measured Simultaneously in Reverberation and Free Fields. Highway 409.